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Nuclear Physics and Related Computational Science R&D for Advanced Fuel Cycle Workshop

August 10-12, 2006 Bethesda, Maryland

Impact of cross-section uncertainties on reactor core *and fuel cycle* calculations

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Nuclear data uncertainties have a potential impact on :

Reactor parameters….

- Criticality (multiplication factor)
- Doppler Reactivity Coefficient
- Coolant Void Reactivity Coefficient
- Reactivity Loss during Irradiation
- Transmutation Potential (i.e. nuclide concentration at the end of irradiation)
- Peak Power Value
- Etc
- **….and fuel cycle parameters:**

- MA Decay Heat in a Repository
- Radiation Source at Fuel Discharge
- Radiotoxicity in a Repository
- Etc

Reactor systems: GNEP, Generation-IV, NGNP

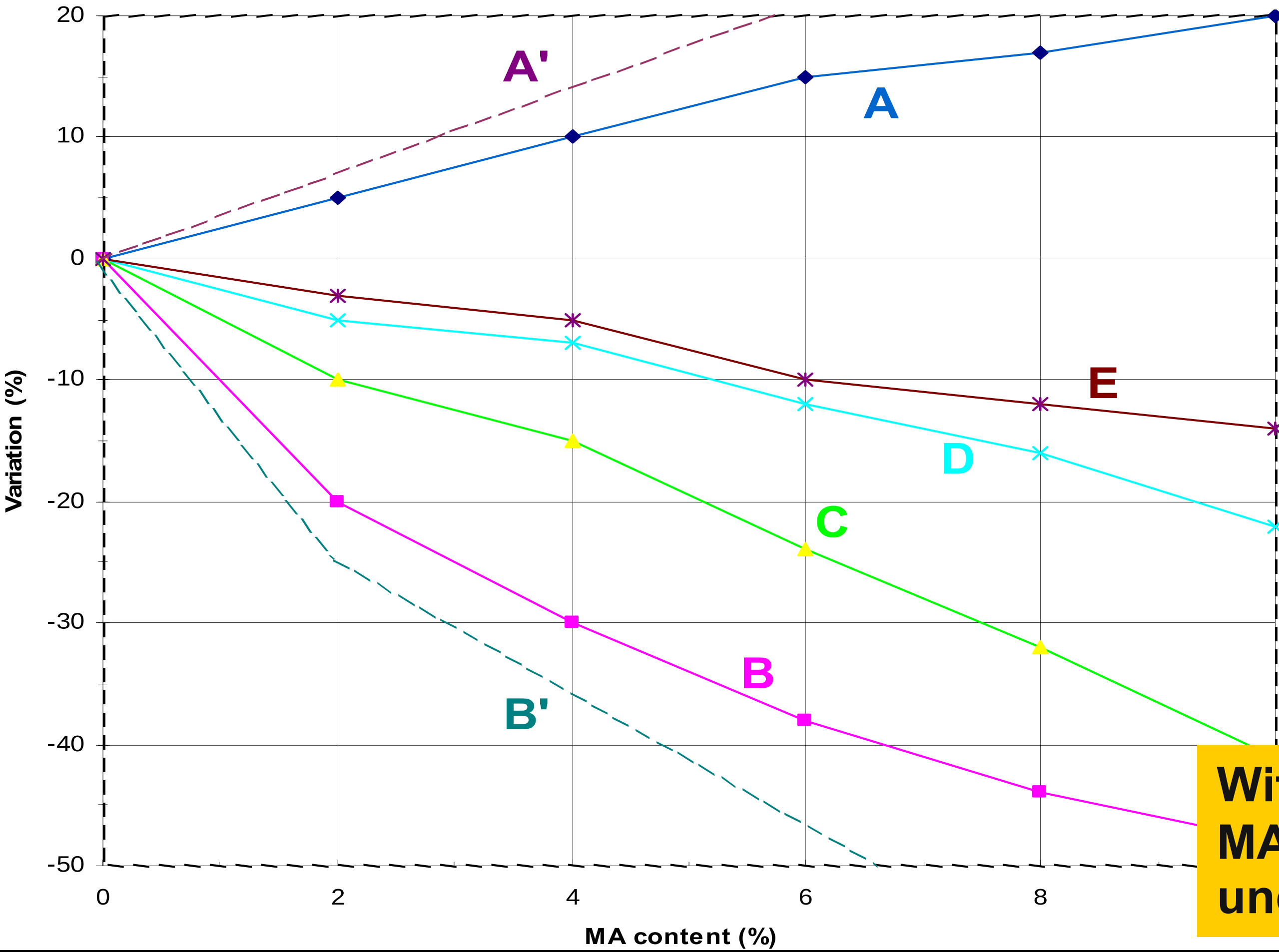
Today for most foreseeable systems, there are no likely show-stoppers due to nuclear data.

For the present phase of pre-conceptual design, most data are available and their quality in most case sufficient for that purpose.

However, in some cases data uncertainties (if taken conservatively) can prevent a full optimization or a clear choice among design options (e.g. in the case of reactivity coefficient evaluation).

IMPACT OF UNCERTAINTIES ON DESIGN

Variation of integral parameters as a function of MA content. Case of a large Na-cooled FR with homogeneous recycling of MA. Impact of uncertainties on max. amount of MA in the fuel?



A - Na-Void coefficient

B - Doppler coefficient

C – $\Delta\rho$ cycle

D - Control rod worth

E - Beta effective

A' - Upper limit of Na void coefficient variation (including uncertainty)

B' - Lower limit of Doppler coefficient variation (including uncertainty)

With nominal values, max MA content is ~4%. With uncertainties: ~3%!!

Coolant void reactivity coeff. uncertainties (%) in a VHTR with molten salt coolant

Breakdown in energy….

Upper Energy	Capture	Scattering	Total
19.6 MeV	13.3	26.7	29.8
6.07	46.1	17.9	49.5
2.23	7.7	6.0	9.8
1.35	1.0	0.7	1.5
0.498	1.6	0.8	2.2
0.183	2.2	1.8	2.9
67 KeV	15.5	4.5	16.2
24.8	3.7	0.7	3.8
9.12	1.6	2.5	3.2
204 eV	3.7	6.6	7.7
45.4	25.2	57.9	63.7
22.6	36.5	75.9	84.2
4.0	16.2	2.1	17.1
0.54	51.8	1.1	53.5
0.1	30.3	0.4	38.6
Total	92.0	101.3	140.0

Large uncertainty: since absolute value is small, sign can be uncertain

Coolant void reactivity coefficient uncertainties (%) in a VHTR with molten salt coolant.

…and by isotope and reaction type

Isotope	Capture	Fission	ν	Scattering	Total
U235	17.8	22.3	19.3	0.0	34.5
U238	41.8	1.2	1.1	0.2	41.9
Si	6.0	0.0	0.0	0.4	6.1
C	11.1	0.0	0.0	87.6	88.3
Li6	48.7	0.0	0.0	0.0	48.7
Li7	32.2	0.0	0.0	13.8	35.0
Be	38.8	0.0	0.0	29.2	48.5
F	36.3	0.0	0.0	39.2	53.5
Total	92.0	22.4	19.3	101.3	140.0

Uncertainty data play also a major role to point out which cross section (isotope, reaction type, energy range) should be improved **to meet design requirements**, as they will be defined in a successive **phase of consolidated design**.

Improvement of selected data (i.e. reduction of uncertainties), **will be crucial** to:

- reduce costly margins in design
- help the safety and licensing case

Further on, data improvements will have impact on the **system operation** (again, by reduction of margins):

There are short term and long term needs!

The approach to evaluate the impact of nuclear cross-section uncertainties and needs for improvement

- **Sensitivity analysis** is performed, e.g. via GPT (Generalized Perturbation Theory), on performance parameters (core, fuel cycle) of representative models of the systems of interest.
- **Uncertainty (e.g. nuclear data covariance)** propagation and assessment

Once the **sensitivity coefficient matrix *S*** and the **covariance matrix *D*** are available, the uncertainty on the integral parameter can be evaluated:

$$\Delta R_0^2 = S_R^+ D S_R$$

- **Impact** on design and **target accuracy requirements** can then be specified as a successive step.

SFR (Burner: CR = 0.25)

840 MW_{th} – Na Cooled

U-TRU-Zr Metallic Alloy Fuel

SS Reflector

Pu content: 56%

MA: 10%

Irradiation Cycle: 155 d

EFR

3600 MW_{th} – Na Cooled

U-TRU Oxide Fuel

U - Blanket

Pu content : 22.7%

MA: 1%

Irradiation Cycle: 1700 d

"GNEP type"

GFR

2400 MWe – He Cooled

SiC – (U-TRU)C Fuel

Zr_3Si_2 Reflector

Pu content : 17%

MA: 5%

Irradiation Cycle: 415 d

LFR

900 MW_{th} – Pb Cooled

U-TRU-Zr Metallic Alloy Fuel

Pb Reflector

Pu content : 21%

MA: 2%

Irradiation Cycle: 310 d

VHTR

TRISO Fuel

U235 Enrichment: 14%

Burnup: 90 GWd/Kg

The systems which have been investigated

Fast Reactors Performance Target Accuracies (1σ)
(as defined within an international working group of the OECD-NEA)

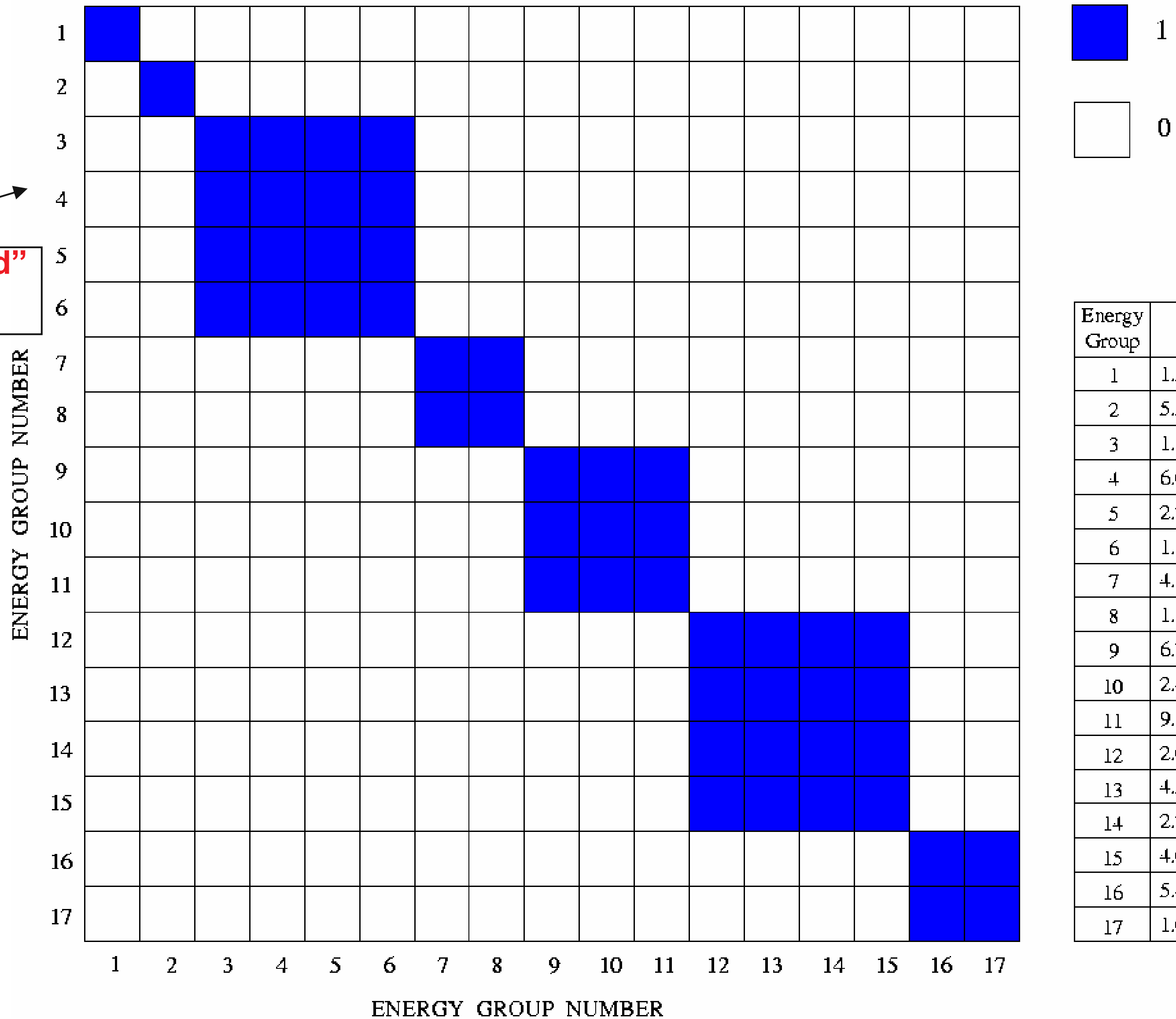
PARAMETER	Q_n^T TARGET ACCURACY (1σ)
Multiplication factor (BOL)	0.3% Δk/k
Peak power (BOL)	2%
Power distribution	3%
Control rod worth (element)	5%
Control rod worth (total)	2%
Burn-up reactivity swing	0.3% Δk/k
Breeding gain	0.02
Coolant void reactivity coefficient (BOL)	7%
Doppler reactivity coefficient (BOL)	7%
Beta effective	5%
Major nuclide density at end of irradiation cycle	2%
Other nuclide density at end of irradiation cycle	10%

Uncertainty Requirements for UO_2- and PuO_2-fuelled HTR's

Parameter	Q_n^T Target accuracy (1 sigma)
Criticality	300 pcm (operation) 500 pcm (safety)
Local power (in fuel compact)	6% (2% in pin-wise fission rate of fresh fuel + 4% in main fissile isotope concentration of irradiated fuel)
Burn-up (cycle length)	0.5-1% (⇒ ~ 500 MWd/t)
Doppler coefficient	20%
Moderator temperature coefficient	1 pcm/°C
Beta-eff	10%
Prompt neutron lifetime	10%
Control rod worth: Integral Differential	10% 15% (locally)
Nuclide inventories at EOL: Main fissile isotopes Fertile isotopes MAs and FPs	4% 5% 20%
Poisons	< 3% (capture)
Shutdown margins	10%
Fuel decay heat	30% (20% on radio-nuclide concentrations + 10% on decay half-lives and energies)

Energy group structure and proposed partial energy correlation.

An “educated” guess!!



Energy Group	MeV
1	1.50000E+2
2	5.51820E+1
3	1.96403E+1
4	6.06531E+0
5	2.23130E+0
6	1.35335E+0
7	4.97871E−1
8	1.83156E−1
9	6.73795E−2
10	2.47875E−2
11	9.11882E−3
12	2.03468E−3
13	4.53999E−4
14	2.26033E−5
15	4.00000E−6
16	5.40000E−7
17	1.00000E−7

1. Despite a significant MA recycling expected in fast systems and extended burn-ups in thermal systems, MA required accuracies are often of the order of 10-20% for most isotope and reaction types.

   However higher accuracy required for:

   - Am-243 capture in „fast“ and „thermal“ range
   - Am-242m fission in the „fast“ range
   - Am-241 capture in the “fast” range (>1keV) and fission

2. As for major actinides, besides U-238 (capture and inelastic), <u>Pu isotope data uncertainties are very significant:</u>

   - Pu-239 fission between 1 MeV and 1 keV and below 1 eV
   - Pu-240 capture at the first resonance
   - Pu-241 fission between 1MeV and 1 keV
   - U-238 capture between 0.2MeV and 2keV and between 400eV and 10eV
   - U-238 inelastic

3. As for structural/coolant materials, uncertainty reductions can have impact:

   - Fe inelastic (if 10-20% uncertainty value is assumed)
   - Na inelastic (if 30% uncertainty)
   - Pb inelastic (if 40% uncertainty)
   - Si inelastic (if 30% uncertainty)

These are preliminary indications, since they depend on the “quality” of the covariance data used.

There is then an urgent need to establish scientifically based covariance data, to give credibility to new data improvement requirements.

However, in the case of major actinides (and in particular for Pu isotopes) the very tight accuracy requirements are expected to be widely confirmed, as well as the requirements for improved inelastic scattering data for most actinides and intermediate mass isotopes.

A general “message”: a few, very high accuracy new measurements can be needed, in particular (still!!) for major actinides and for selected minor actinides, often at the limit of the performances of present experimental techniques. This can point out to the need of using integral experiments of very high accuracy and performing statistical data adjustments.

Statistical Data Adjustment

When a set of calculated integral parameters Q_i (which are function of nuclear data σ_j) and the corresponding experimental values Q_i^{ex} are available, ERANOS evaluates the best estimates ("adjustments") of σ_j , given the covariance matrices of the σ and of the experiments Q_i.

If we define: $y_j=(\sigma_j^{adj}- \sigma_j)/\sigma_j$ and $y_{Qi}^{exp}=(Q_i^{exp}- Q_i)/ Q_i$, the y_j are given by:

$$\overline{\mathbf{y}} = \left(\mathbf{S}^{\mathrm{T}}\mathbf{D}_{\mathbf{Q}}^{-1}\mathbf{S} + \mathbf{D}^{-1}\right)^{-1} \mathbf{S}^{\mathrm{T}}\mathbf{D}_{\mathbf{Q}}^{-1}\, \overline{\mathbf{y}}_{\mathbf{Q}}^{\mathbf{exp}}$$

where D_Q is the covariance matrix of the experiments, D the covariance matrix of the cross sections and S is the sensitivity matrix.

It will also result an adjusted covariance matrix for the nuclear data:

$$\left(\mathbf{D}^{\mathbf{adj}}\right)^{-1} = \mathbf{D}^{-1} + \mathbf{S}^{\mathrm{T}}\mathbf{D}_{\mathbf{Q}}^{-1}\,\mathbf{S}$$

This new matrix will replace the initial D matrix in the data base.

Note: in principle the adjustment procedure can be applied to nuclear model parameters!

Besides neutron interaction data, other relevant data will very probably need improvement:

Decay Data Evaluations

- The measured data for some isotope is incomplete, and for some there are no measured values.
- In some cases integral decay properties have been measured (mean beta and gamma energies).
- Theoretical estimates have been made and these could be included in the absence of measured data.
- Adjustment of data to fit the integral measurements is another possibility.
- How is the balance to be struck between including only "good quality" data, based on an evaluation of the measurements, and completeness?

Fission Product Yield Evaluations

- The ensemble of the measured data have been adjusted, within the uncertainties, to satisfy conservation laws. However, the uncertainties assumed for some key fission monitors isotopes in the adjustment process were too large, or that these yields should be constrained in some way.
- The evaluation methodology has been improved. E.g. improvements have been made (and are still in progress) to the data base of measured values, the decay data used to calculate isomeric splitting and cumulative yields and uncertainties.

Delayed neutron fraction β for selected nuclides

Nuclide	β
^{238}U	0.0158
^{235}U	0.00680
^{237}Np	0.00437
^{239}Pu	0.00215
^{240}Pu	0.00310
^{241}Pu	0.00515
^{242}Pu	0.00720
^{241}Am	0.00138
^{243}Am	0.00230
^{242}Cm	0.00033

The presence in the fuel of a high content of MA lowers the effective delayed neutron fraction, making the reactor control more delicate.

Higher accuracy data are needed.

Thermal Scattering Data

- Scattering dynamics models for H in H_2O, D in D_2O, C in graphite, Be in beryllium and H in polyethylene at a range of temperatures have been used to produce S(a,b) data on a fine mesh. Extensive comparisons were made with experiment.
- Recently, thermal scattering data for H in ZrH and H in CaH_2 have also been produced. These are of interest in connection with studies using moderated assemblies for actinide incineration in fast reactors.
- However, changes in microstructure e.g. of graphite during irradiation, can affect thermal scattering (e.g. via phonon distribution).
- This can affect spectrum in a VHTR and have impact on safety and performance parameters.

Photon production data

- Gamma production data are of relevance for power distribution assessment in particular at interfaces (e.g. core/reflector) of innovative burner reactors. Improved evaluation and possibly experiments, are still needed

Investigations of Method Approximations

- There are still some approximations in the treatment of temperature effects which should be given consideration: secondary energy distributions in resonances and the influence of solid state effects are only treated approximately and there could be other approximations which require further study.

Conclusions

- The mechanisms of the impact of data uncertainties on reactor core and fuel cycle are well understood. Powerful algorithms and code systems are available

- The uncertainty impact is different at different stages of a reactor system design:

  In a pre-conceptual design phase, even if present uncertainties have a limited impact, they can affect crucial design choices.

  In more advanced phases, uncertainty reduction and data improvement plays an even more relevant role:

  There are short and long term objectives

- There is an urgent need to establish on a sound base covariance data for the most important isotopes. Work is in progress in several laboratories and the outcome is much expected.

- However, there are already indications (and in some cases, quantitative) of major areas for improvement to meet the requirements of Advanced Fuel Cycles:

  Pu isotope data, and in particular fission
  U-238 inelastic
  Am isotope data
  Decay heat related data and delayed neutron for MA
  Thermal scattering data (e.g. for graphite), photon production data

BACK-UP

Results of preliminary analysis: FR

Fast Reactors

Total 1σ Uncertainties (%)

Reactor		K_{eff}	Power Peak	Doppler coeff	Void coeff	Burnup $\Delta\rho$ (10^{-5} $\Delta k/k$)	Decay Heat	Dose	Neutron Source
GFR	No Correlation	±1.21	±1.2	±4.4	±5.2	±238	±0.3	±0.4	±1.2
	PEC	1.92	1.8	6.8	7.7	381	0.5	0.6	1.8
LFR	PEC	2.26	1.0	9.1	13.6	251	0.6	0.5	1.2
SFR	PEC	1.75	0.5	7.7	19.5	217	0.4	0.2	0.9
EFR	PEC	1.74	1.1	6.7	11.8	979	2.3	1.7	6.0

PEC: Partial Energy Correlations

SFR

Uncertainties (%) PEC – Breakdown by Isotope (Major Contributions)

Isotope	K_{eff}	Doppler	Void	Burnup [10^{-5} $\Delta k/k$]
U238	±0.21	±0.8	±1.9	±15
Pu238	0.34	1.1	3.8	53
Pu239	0.88	2.5	5.5	99
Pu240	0.52	1.3	4.4	45
Pu241	0.51	1.7	4.3	109
Pu242	0.23	0.6	1.6	21
Am241	0.13	0.8	1.2	7
Am242m	0.64	1.9	4.1	89
Cm242	0.04	0.1	0.3	15
Cm244	0.36	1.1	2.8	58
Cm245	0.37	1.2	3.0	64
Fe56	0.62	2.9	8.3	45
Na23	0.34	2.4	18.7	30

SFR

K_{eff} Uncertainties. Energy breakdown [10^{-5} $\Delta k/k$]

Gr.	Energy	Pu^{238} σ_{fiss}	Pu^{239} σ_{fiss}	Pu^{240} σ_{fiss}	Pu^{241} σ_{fiss}	Am^{242m} σ_{fiss}	Cm^{244} σ_{fiss}	Fe^{56} σ_{in}	Na^{23} σ_{in}
1	19.6 MeV	±4	±7	±9	±6	±3	±8	±30	±9
2	6.07 MeV	36	76	81	59	39	75	111	51
3	2.23 MeV	40	87	89	37	38	75	114	42
4	1.35 MeV	113	261	185	109	138	189	242	238
5	498 KeV	94	351	42	180	262	33	0	1
6	183 KeV	50	293	18	183	258	9	0	0
7	67.4 KeV	90	148	10	111	152	5	0	0
8	24.8 KeV	80	118	6	101	70	4	0	0
9	9.12 KeV	35	43	3	43	29	1	0	0
10	2.03 KeV	64	44	8	65	47	2	0	0
11	454 eV	11	13	0	17	11	0	0	0
12	22.6 eV	0	1	0	3	1	0	0	0
13	4.00 eV	0	0	0	0	1	0	0	0
14	0.54 eV	0	0	0	0	0	0	0	0
15	0.10 eV	0	0	0	0	0	0	0	0
Total [pcm]		217	575	227	334	434	220	291	247

Results of preliminary analysis: VHTR

VHTR

Total 1σ Uncertainties (%)

	K_{eff} BOC	K_{eff} EOC	Peak Power BOC	Peak Power EOC	Doppler BOC	Doppler EOC	Burnup [10^{-5} Δk/k]	Decay Heat	Dose	Neutron Source
PEC	0.58	1.07	1.9	2.1	3.1	6.1	1749	3.1	2.6	14.3

BOC: Beginning Of irradiation Cycle
EOC: End Of irradiation Cycle

VHTR

Uncertainties (%) PEC – Breakdown by Isotope (Major Contributions)

Isotope	Keff		Doppler		Burnup [$10^{-5}\Delta k/k$]	Neutron Source
	BOC	EOC	BOC	EOC		
U235	±0.36	±0.25	±1.3	±0.6	±171	±0.02
U238	0.43	0.55	2.7	2.2	150	2.61
Pu239	0.00	0.57	0.0	3.0	624	2.26
Pu240	0.00	0.63	0.0	3.9	1313	2.60
Pu241	0.00	0.17	0.0	0.3	222	2.33
Pu242	0.00	0.02	0.0	0.1	36	3.95
Am243	0.00	0.02	0.0	0.1	27	12.60
Cm244	0.00	0.00	0.0	0.0	3	2.30

Results of the Target Accuracy Analysis

GFR

Isotope	Cross Section	Energy Range	Uncertainty % Initial	Uncertainty % Required
Pu239	σ_{capt}	183 KeV-67.4 KeV	15	8.1
		24.8 KeV-9.12 KeV	10	6
		9.12 KeV-2.03 KeV	5	4.1
		2.03 KeV-454 eV	5	4.5
	σ_{fiss}	6.07 MeV-2.23 MeV	5	3.3
		2.23 MeV-1.35 MeV	5	3.2
		1.35 MeV-498 KeV	5	2
		498 KeV-183 KeV	5	2
		183 KeV-67.4 KeV	5	1.8
		67.4 KeV-24.8 KeV	5	2
		24.8 KeV-9.12 KeV	5	2.2
		9.12 KeV-2.03 KeV	5	1.9
		2.03 KeV-454 eV	3	2.3

SFR

Isotope	Cross Section	Energy Range	Uncertainty % Initial	Uncertainty % Required
Pu239	σ_{capt}	498 KeV-183 KeV	15	9.4
		183 KeV-67.4 KeV	15	8.1
		67.4 KeV-24.8 KeV	10	9
		24.8 KeV-9.12 KeV	10	7.7
	σ_{fiss}	6.07 MeV-2.23 MeV	5	3.9
		2.23 MeV-1.35 MeV	5	3.6
		1.35 MeV-498 KeV	5	2.1
		498 KeV-183 KeV	5	1.8
		183 KeV-67.4 KeV	5	2
		67.4 KeV-24.8 KeV	5	2.8
		24.8 KeV-9.12 KeV	5	3.1

EFR

Isotope	Cross Section	Energy Range	Uncertainty % Initial	Uncertainty % Required
Pu239	σ_{capt}	1.35 MeV-498 KeV	15	12
		498 KeV-183 KeV	15	7.1
		183 KeV-67.4 KeV	15	5.3
		67.4 KeV-24.8 KeV	10	5
		24.8 KeV-9.12 KeV	10	4.4
		9.12 KeV-2.03 KeV	5	4.1
		2.03 KeV-454 eV	5	3.4
	σ_{fiss}	6.07 MeV-2.23 MeV	5	3.4
		2.23 MeV-1.35 MeV	5	3.4
		1.35 MeV-498 KeV	5	1.9
		498 KeV-183 KeV	5	1.8
		183 KeV-67.4 KeV	5	1.7
		67.4 KeV-24.8 KeV	5	2
		24.8 KeV-9.12 KeV	5	2.3
		9.12 KeV-2.03 KeV	5	2.7
		2.03 KeV-454 eV	3	2.2
	$\sigma_{n,2n}$	19.6 MeV-6.07 MeV	50	32.4

The case of Pu-239 data…..

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Results of the Target Accuracy Analysis

GFR

Isotope	Cross Section	Energy Range	Uncertainty % Initial	Uncertainty % Required
Pu241	σ_{fiss}	6.07 MeV-2.23 MeV	20	8.4
		1.35 MeV-498 KeV	10	5
		498 KeV-183 KeV	10	4.5
		183 KeV-67.4 KeV	10	3.7
		67.4 KeV-24.8 KeV	10	3.7
		24.8 KeV-9.12 KeV	10	3.8
		9.12 KeV-2.03 KeV	10	3.2
		2.03 KeV-454 eV	10	4

SFR

Isotope	Cross Section	Energy Range	Uncertainty % Initial	Uncertainty % Required
Pu241	σ_{fiss}	6.07 MeV-2.23 MeV	20	8.8
		2.23 MeV-1.35 MeV	10	7.8
		1.35 MeV-498 KeV	10	4.6
		498 KeV-183 KeV	10	3.6
		183 KeV-67.4 KeV	10	3.5
		67.4 KeV-24.8 KeV	10	4.5
		24.8 KeV-9.12 KeV	10	4.7
		9.12 KeV-2.03 KeV	10	7.3
		2.03 KeV-454 eV	10	6

EFR

Isotope	Cross Section	Energy Range	Uncertainty % Initial	Uncertainty % Required
Pu241	σ_{capt}	24.8 KeV-9.12 KeV	20	14.5
		9.12 KeV-2.03 KeV	20	15.3
		2.03 KeV-454 eV	20	13
	σ_{fiss}	6.07 MeV-2.23 MeV	20	10.6
		2.23 MeV-1.35 MeV	10	9.9
		1.35 MeV-498 KeV	10	5.7
		498 KeV-183 KeV	10	4.5
		183 KeV-67.4 KeV	10	3.8
		67.4 KeV-24.8 KeV	10	4.1
		24.8 KeV-9.12 KeV	10	4.3
		9.12 KeV-2.03 KeV	10	4.8
		2.03 KeV-454 eV	10	4.3

….the case of Pu-241….

Results of the Target Accuracy Analysis

GFR

Isotope	Cross Section	Energy Range	Uncertainty %	
			Initial	Required
Am241	σ_{capt}	183 KeV-67.4 KeV	10	5.1
		67.4 KeV-24.8 KeV	10	4.9
		24.8 KeV-9.12 KeV	10	5
		9.12 KeV-2.03 KeV	10	4.2
		2.03 KeV-454 eV	10	4.8
	σ_{fiss}	6.07 MeV-2.23 MeV	10	4.7
		2.23 MeV-1.35 MeV	10	4.7
		1.35 MeV-498 KeV	10	4.4

EFR

Isotope	Cross Section	Energy Range	Uncertainty %	
			Initial	Required
Am241	σcapt	183 KeV-67.4 KeV	10	9.8
Am242m	σcapt	183 KeV-67.4 KeV	40	32.7
	σ_{fiss}	183 KeV-67.4 KeV	20	19.4
		67.4 KeV-24.8 KeV	20	19.2

SFR

Isotope	Cross Section	Energy Range	Uncertainty %	
			Initial	Required
Am241	σ_{capt}	498 KeV-183 KeV	10	9.2
		183 KeV-67.4 KeV	10	8.3
	σ_{fiss}	6.07 MeV-2.23 MeV	10	9.3
		2.23 MeV-1.35 MeV	10	8.7
		1.35 MeV-498 KeV	10	7.9
Am242m	σ_{capt}	498 KeV-183 KeV	40	19.8
		183 KeV-67.4 KeV	40	15.7
	σ_{fiss}	6.07 MeV-2.23 MeV	20	11.1
		2.23 MeV-1.35 MeV	20	11.3
		1.35 MeV-498 KeV	20	5.8
		498 KeV-183 KeV	20	4.2
		183 KeV-67.4 KeV	20	4.2
		67.4 KeV-24.8 KeV	20	5.5
		24.8 KeV-9.12 KeV	10	5.7
		9.12 KeV-2.03 KeV	10	8.8
		2.03 KeV-454 eV	10	7

….and the case of higher mass Actinides.

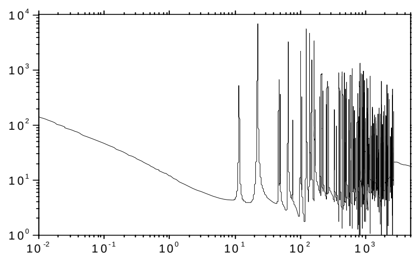
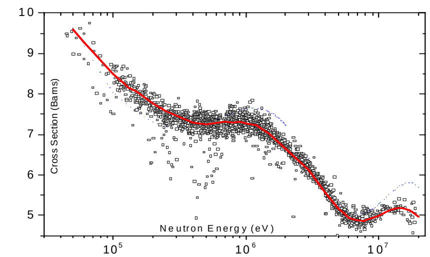
Remember: GFR: 5% MA EFR: 1% MA SFR: 10% MA

Case of a VHTR: required cross-section uncertainties to meet design target accuracies (e.g. ≤ 0.5% Δk/k on the reactivity loss/cycle)

Isotope	Cross Section	Energy Range	Uncertainty %		Isotope	Cross Section	Energy Range	Uncertainty %	
			Initial	Required				Initial	Required
U236	σ_{capt}	22.6 eV-4.00 eV	8	7.1	Pu241	σ_{fiss}	454 eV-22.6 eV	10	8.1
U238	σ_{capt}	454 eV-22.6 eV	3	1.9			22.6 eV-4.00 eV	10	5.5
		22.6 eV-4.00 eV	3	1.4			0.54 eV-0.10 eV	2	1.9
Pu239	σ_{capt}	0.54 eV-0.10 eV	3	1.1	Am241	σ_{capt}	0.54 eV-0.10 eV	10	9.4
	σ_{fiss}	0.54 eV-0.10 eV	2	1	Am243	σ_{capt}	4.00 eV-0.54 eV	20	12.4
Pu240	σ_{capt}	454 eV-22.6 eV	10	9.6	C	σ_{scatt}	6.07 MeV-2.23 MeV	35	12.3
		4.00 eV-0.54 eV	7	1.1					

A general "message": a few, very high accuracy new measurements can be needed, in particular (still!!) for major actinides and for selected minor actinides, often at the limit of the performances of present experimental techniques!!

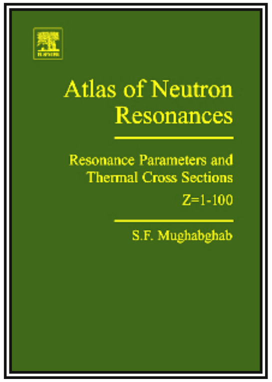
Methodology for covariance calculations at BNL

<table>
<tr><td colspan="3">Pointwise cross sections (with any energy groups)</td></tr>
<tr><td>RRR
(Resolved Resonance Region)</td><td>URR
(Unresolved Resonance Region)</td><td>FaR
(Fast Region)</td></tr>
<tr><td>
</td><td colspan="2">EMPIRE + KALMAN</td></tr>
<tr><td colspan="2">Resonance Module + KALMAN</td><td>
</td></tr>
</table>

General Procedure

RIPL
&
Parameter uncertainty adjustment

or



Parameters

Uncertainty

Optional:
Thermal neutron capture

Resonance Integral

Models and parameters

- -Fast Region
  - -Hauser Feshbach
  - -Pre-equilibrium
  - -…
- -Resonance Region
  - -Breit Wigner
  - -Reich Moore

Parameters

Sensitivity

KALMAN Filter

an optimal recursive data processing algorithm

Cross Section Uncertainties and Cross Section Correlations